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Discussion: Remoulded shear strength at plastic and semi-solid states

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Vinod *et al.* (2012) have presented valuable data on strength variation with water content. There are, however, several points that we would like to make regarding the assessment of strengths at and beyond the Atterberg limits.

The authors attempted to measure soil strength both in the plastic range and in the brittle 'semi-solid' range using a vane shear apparatus. The vane shear test involves inserting a vane into a soil sample and measuring the resistance to rotation. The data are conventionally analysed by assuming that a constant shear stress is exerted over the entire surface area of the cylinder of rotating soil (ASTM, 2000). While this is appropriate for plastic materials in which strength will approach maximum strength at large strain, for brittle materials the variation in strain over the base of the cylinder will result in peak strengths not being achieved simultaneously. The maximum torque, when converted to a shear stress, will hence underestimate the peak strength of the soil. Further problems may also be created as the vane is inserted into the soil sample.

ASTM D 4648-00 (ASTM, 2000) asserts that: 'The remoulded zone around a vane blade is generally assumed to be small and have little or no effect on the stress–strain properties of the sediment being tested.' This assertion is again valid only for plastic materials; the process of inserting the vane must result in yielding of the soil. For a brittle material this will result in cracking of the soil sample, and hence an underestimate of peak strength during subsequent shearing of the soil.

As soils at water contents less than the plastic limit are by definition brittle, strengths measured using the vane shear apparatus at these water contents should be treated with caution. Strengths measured in triaxial compression, allowing constant strain to be accumulated within the sample and observation of the entire stress–strain relationship, would be a more appropriate approach.

The strength observed at plastic limit for the nine soils tested is approximately 161 kPa, very similar to that predicted by Wroth and Wood (1978). As shown by Haigh *et al.* (2012) and Nagaraj *et al.* (2012), plastic limit does not correspond to a fixed soil strength, merely to the onset of brittleness. Based on a data set of 71 strengths at plastic limit reported in the literature, Haigh *et al.* (2012) showed that the strength at plastic limit had a range of 17–530 kPa, with an average value of 152 kPa and a standard deviation of 89 kPa. While the data for nine soils presented by Vinod *et al.* (2012) fall centrally within this range, it would be wrong to assume that the small scatter of strengths found was representative of a wide range of soils.

The strengths observed at liquid limit were consistently found to be 5·8 kPa, much greater than the commonly reported range of 0·7–2·65 kPa (Wroth and Wood, 1978). It is unclear from the paper whether liquid limits were obtained using the fall-cone or Casagrande cup apparatus, which has a potential impact on the soil strength at the liquid limit. Using the fall-cone liquid limit, undrained strength might be expected to be approximately 1·7 kPa (Wroth and Wood, 1978), whereas at the Casagrande cup liquid limit the specific strength (strength divided by density) might be expected to be approximately 1 m^2/s^2 (Haigh, 2012), implying a range of strengths between 1·41 and 1·76 kPa for the range of soils presented. In either case 5·8 kPa appears excessive, calling into question the liquid limit values obtained. It is interesting to note that if the liquid limit were reinterpreted as being the point on the trendline at which the soil strength was 1·7 kPa, the regression relationship would become

$$7. \qquad c_u = 161{\cdot}3 \exp^{-4{\cdot}55 I_L}$$

almost identical to the expression given by Wroth and Wood (1978).

While the paper has offered strong evidence of the exponential relationship between strength and water content in the plastic region, more evidence would be required to use the expression derived with confidence for the prediction of soil strength. While we have also expressed concerns with regard to the methodology used to determine the variation of strength for soils at water contents below the plastic limit, similar trends shown are also reflected in the data presented by Marinho and Oliviera (2012) for compacted soils. With additional testing, this paper may prove to have offered a valuable insight into the strengths of these brittle materials.

Authors' reply

The authors thank the discussers for their comments, and appreciate the contributions they have made to the understanding of the mechanics of liquid limit and plastic limit tests (Haigh, 2012; Haigh *et al.*, 2012). However, the authors have certain points on which they differ from the views of the discussers, which are described below.

The discussers have commented at length on the applicability of the vane shear test for determination of the undrained shear strength of soils in the semi-solid state. Many of their statements are valid. However, the prime objective of the authors was to highlight the noticeable transition in the semi-solid state, in the variation pattern of the undrained shear strength–water content relationship of soils, from the well-known behaviour in the plastic state. As a first attempt to investigate the relationship in the semi-solid state, the authors felt that the laboratory vane test was an adequate device for the role. The empiricism in the determination of engineering behaviour of soils that has been discussed by Burland (1987, 2006) is inevitable, and is useful in geotechnical engineering situations such as that in the vane shear test, where the peak shear strength is not mobilised simultaneously over the entire soil surface. At the same time, the authors agree with the discussers' point that strengths measured in triaxial compression, where the entire stress–strain relationship may be observed, would be a more appropriate approach.

It is also recognised that the observed soil strengths at the plastic limit reported in the literature (e.g. Haigh *et al.*, 2012; Nagaraj *et al.*, 2012) show a wide scatter. The mechanism controlling the plastic limit of fine-grained soils and the clay mineralogy effect are not clear. The stress state during the thread-rolling plastic limit test is known to be complex, owing to the lack of control on applied stresses during the test (Whyte, 1982). At the same time, even though it is agreed that the 3 mm thread-rolling method may not yield accurately reproducible results, the method still measures the soil plastic limit controlled by cohesion, which cannot be measured by the fall-cone test, wherein the controlling mechanism is undrained friction (Prakash and Sridharan, 2006). Prakash *et al.* (2009) have shown that reproducible and reliable results can be obtained even with the 3 mm thread-rolling method, if the test is conducted by an experienced person. It is accepted that the difference between the liquid limit and the plastic limit, which represents the range of plasticity of a fine-grained soil, is due to the mouldability of the soil, and therefore is controlled by the soil cohesion. The plasticity properties are invariably to be measured by those tests where the factors controlling plasticity come into play.

As far as the determination of liquid limit is concerned, it has been hypothesised that the liquid limit obtained from the percussion method is controlled primarily by viscous shear resistance due to the diffuse, double-layer-held water, and the cone method is essentially governed by undrained frictional shear resistance at the particle level. Detailed discussion on the mechanisms controlling the above two methods of determination of liquid limit are reported elsewhere (Sridharan and Prakash, 1998; Sridharan *et al.*, 1986, 1988). There is a good match between the mechanism controlling the liquid limit of montmorillonite soils (i.e. thickness of the diffuse double layer) and the dominant mechanism in the percussion method (i.e. viscous shear resistance due to diffuse double-layer water). Similarly, there is good agreement between the mechanism controlling the liquid limit of kaolinitic soils (i.e. the mode of particle arrangement and the shear resistance at the particle level) and the dominant mechanism in the cone method (i.e. frictional resistance at the particle level). In view of the above, the authors used the percussion method for the liquid limit determination of bentonite, Cochin marine clay and Kuttanad clay, whereas the cone method was used for Chittoor clay, Malappuram clay, Palakkad clay, Thonnackal clay, lateritic soil and kaolinite.

The observed values of shear strengths at the liquid limit in the study are higher than most of the reported values. This may be due to the sensitivity in the determination of shear strength at water contents close to the liquid limit, irrespective of the method adopted.

Although the discussers have welcomed the strong evidence of the exponential relationship between shear strength and water content, they have expressed concerns over its practical applicability. As in any other research work, more evidence would be required to use the expressions derived with confidence for the prediction of soil strength, particularly for soil in the semi-solid state. Further refinements can be made by using a large body of data of shear strengths.

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